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Changes in Soil Properties and Scots Pine Tree Growth Induced by Different Soil Ploughing Prior to Afforestation: A Case Study

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Abstract: Numerous studies have confirmed that forests have the potential for a significant contribution to carbon sequestration, but afforestation of former agricultural land can be attempted to adopt technologies that further encourage carbon sequestration. The aim of this study was to evaluate the impact of different soil cultivation methods, including deep ploughing and soil cultivation by making microsites and furrows prior to afforestation of former agricultural land, on chemical soil properties and tree growth in 20 years old Scots pine plantations. A naturally regenerated Scots pine stand, representing the non-ploughed soil, was included as a control site. Deep ploughing, among other soil cultivation methods, significantly altered the chemical soil properties. Furthermore, significant effects were indicated in the sites afforested after cultivation by making furrows. A recent study found that, due to deep soil cultivation, higher stocks of soil organic carbon (SOC) and total nitrogen (N) were incorporated into deeper soil layers and were protected from direct environmental impact. Twenty years post afforestation in deeply ploughed sites, we still found a decreased C:N ratio and disbalanced relationship between the concentrations of SOC and total N. The SOC and total N stocks were higher in the subsoil than in the topsoil in the sites afforested after deep ploughing. Moreover, deep ploughing and soil cultivation by furrows prior to afforestation resulted in higher total SOC and total N stocks in the forest floor and mineral 0–80 cm soil layer. A higher total phosphorus (P) concentration in the subsoil and total potassium (K) in the upper mineral soil layer were obtained in the deep ploughing sites and the sites, cultivated by furrows, compared to the non-ploughed sites. Significantly higher total P stock per entire profile was found for the deep ploughing sites and the sites cultivated by furrows than in the naturally regenerated stand. Different soil cultivation methods caused no differences in tree diameter at breast height (DBH) in 20 years old Scots pine stands both in the afforested sites and in the naturally regenerated forest. However, significantly larger tree height in all afforested sites than in the naturally regenerated Scots pine stands was obtained. A lower differentiation in tree DBH was obtained in the deep ploughing sites.

Keywords: *Pinus sylvestris*; deep ploughing; soil organic carbon; soil nutrients; tree height

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1. Introduction

Afforestation of former arable (abandoned or degraded) agricultural land is an important land management technique for carbon (C) sequestration and biodiversity [1–4]. A significant increase in total ecosystem C after afforestation was reported by several studies [2,5,6]. Over a different period, the afforestation of arable land impacts higher C stocks via C sequestration in tree biomass; input of litterfall and subsequent development of forest floor result in higher soil organic carbon (SOC) reserves in forests compared to croplands. In the afforested sites, soil organic matter tends to accumulate more intensively, and the C sequestration in the forest floor is determined [1,7,8]. In the longer term, C sequestration is associated with the C content in the mineral topsoil layers. Nevertheless, mineral soil below 30 cm accumulates 30–75% of total SOC, and this is a very important part of total forest C balance [9–12]. Overall, the establishment of forest plantations removes CO_2 from the atmosphere by storing C in soil and biomass. However, C content in mineral soils does not change in the first decades or even decreases following afforestation [13]. Recent studies on afforestation conducted in the region indicated that the new forest plantations established on agricultural land did not cause a significant increase in SOC stocks in the mineral 0–30 cm topsoil during the first 30 years period [8,14]. Analysis of the relationship between soil tillage technologies and changes in SOC showed that C stocks increase below the plough layer [15]. Furthermore, there is a knowledge gap in the data at deeper soil horizons.

Soil cultivation is an important stage of afforestation, primarily causing disturbance to the physical and chemical properties of the soil [16–19]. Following the sustainability issues, various afforestation and land cultivation techniques have been considered. However, to date, data on the effects of different soil cultivation methods on forest floor development, soil properties, and tree growth are limited.

Deep ploughing has a strong effect on the soil profile, mainly due to the ploughing of the soil to a depth of 30–45 cm or even deeper, up to a depth of 60 cm [16,20–22]. This soil cultivation method was mainly used in agriculture for several decades [20] with some efforts to use it for afforestation sites in Europe. In some cases, deep soil ploughing is limited by environmental constraints. However, if a layer of compacted soil has occurred due to soil cultivation of previous agricultural soil management, afforestation after deeper soil ploughing could improve the water penetration and root growth [23]. Other techniques, such as soil cultivation by making mineral microsites or furrows up to 30 cm depth applied before afforestation, probably should not cause such a strong effect on soil properties. It should also be noted that deep ploughing is one of the quick ways and tools to allow SOC to reach the subsoil by burying it [18]. Soil C sequestration in the deeper layers for a longer period could also be an important issue as the stronger climate warming could intensify soil respiration [24,25].

Recently, increasing the forest area in Lithuania has been the main priority of politicians, and the first intensive period of afforestation began in 1990–2000. Abandoned lands and lands not suitable to be used for agricultural activities were preferred to be afforested. In this context, Lithuania was regarded as a good proxy for the Baltic region, and the project “Afforestation of abandoned agricultural land based on sustainable land-use planning and environmentally sound forest management” was implemented in 1999–2001, as a cooperation between Denmark and Lithuania [26]. The pilot areas were established to test afforestation techniques under various conditions with the commitment to assess the long-term effects of afforestation. This study investigates the effects of different soil cultivation methods, including deep ploughing and soil cultivation by making microsites and furrows before the afforestation of agricultural land, on the forest floor and mineral soil, as well as tree growth 20 years post afforestation.

2. Material and Methods

2.1. Study Area

The study was carried out in southern Lithuania, in the Druskininkai district (54°40′ N; 23°39′ E). For estimation of soil properties and tree growth under different soil cultivation methods, four 20 years old Scots pine (*Pinus sylvestris* L.) plantations were sampled in August–November 2021. These forest plantations were established after the application of different soil cultivation methods prior to afforestation as a part of the Danish–Lithuanian project “Afforestation of abandoned agricultural land based on sustainable land-use planning and environmentally sound forest management” in 2000. The selected sites represent three different soil cultivation methods applied prior to the afforestation of former agricultural land: (1) deep soil ploughing up to 60 cm depth; (2) soil cultivation by 40 cm × 40 cm microsites; (3) soil ploughing by making furrows up to 20 cm depth (Table 1).

Table 1. Characteristics of Scots pine plantations in 2021.

Site Code	Soil Cultivation Method	Size (ha)	Species Composition (Percent)	Planting Density	Stand Densityat Assessment	Number of Assessed Trees
				(Trees·ha^{-1})		
1-Afforested	Deep ploughing, up to 60 cm depth	1.2	90 P ** + 10 B	3200 P + 680 B	2300	183
2-Afforested	Microsites, 40 cm × 40 cm	1.1	90 P + 10 B	2700 P + 560 B	1900	142
3-Afforested	Furrows, up to 20 cm in depth	2.4	100 P	3700 P + 780 B	1500	186
4-Regenerated *	Non-ploughed	1.5	100 P	No planting	1400	120

* Naturally regenerated Scots pine stand was selected as a control stand. ** P—Scots pine; B—silver birch.

One year old Scots pine and silver birch (*Betula pendula* Roth.) seedlings were planted between the furrows at a spacing of 2.2 m × 1.2 m after deep soil ploughing up to 60 cm depth in the first site. In the second site, the seedlings were planted in the middle of the microsite at the spacing of 2.2 m × 1.4 m. In the third site, the seedlings were planted between the furrows at a spacing of 2.2 m × 1.0 m. These three sites were afforested in April 2000. Prior to afforestation, this land was used for agricultural purposes. Cereals and buckwheat were grown until 1991; later, this land was used as a pasture for grazing livestock.

The fourth selected site represented a naturally regenerated forest stand growing on non-ploughed soil (Table 1). Natural seed-based forest regeneration on former agricultural land started approximately in 2000. This Scots pine stand was successfully regenerated, receiving a supply of seeds from the adjacent 50 years old forest.

The total study area was 6.2 ha, including 4.7 ha of afforested sites with different soil cultivation, and 1.5 ha of naturally regenerated Scots pine forest on non-ploughed soil (Table 1; Figure 1).

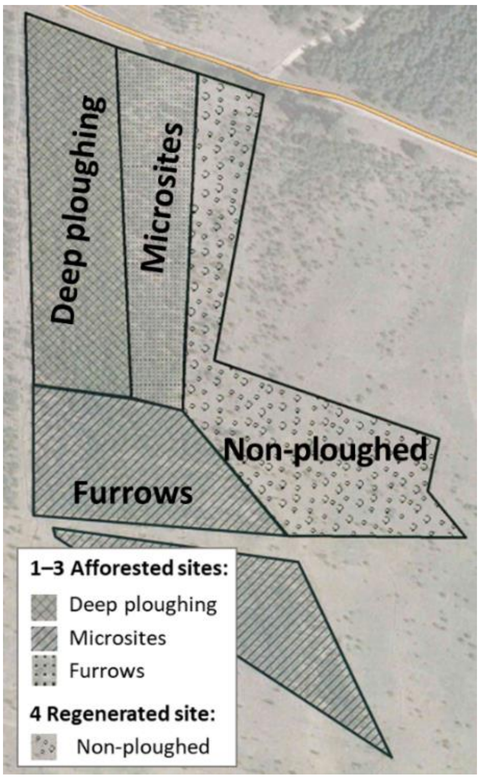

Figure 1. The scheme of the experimental site.

The average annual temperature was 7.4 °C, and the average annual precipitation was 675 mm over the period of 1991–2020. The forest site type in the study area was a normal moisture regime moderately fertile with light soil texture sandy soil [27]; the soils were classified as Arenosols [28].

2.2. Soil Sampling and Chemical Analyses

The chemical properties of the soil were not analyzed before the afforestation of this agricultural land, and the changes observed in this study can only be analyzed in comparison with non-ploughed soil.

For this study, the forest floor for mass determination was sampled with a specific metal frame of 25 cm × 25 cm. In the field, the four samples of the forest floor were composed of five subsamples, transported to the laboratory, dried at 105 °C to a constant mass, and weighed. The soil was sampled from the 0–10 cm, 10–20 cm, 20–40 cm, and 40–80 cm mineral soil layers in August–November 2021. For soil sampling, a metallic soil auger was used. For this study, four composite samples were combined from five subsamples and collected systematically in each of the four sites: deep ploughing, microsites, furrows, and non-ploughed soil.

For the determination of bulk density (g·cm^{-3}) of fine (<2 mm) mineral soil, the four composite samples of mineral soil (0–10 cm, 10–20 cm, 20–40 cm, and 40–80 cm) were taken from five subsamples using a metal cylinder (undisturbed sample of known volume). The samples were passed through a 2 mm sieve to remove stones and gravel; then, the samples were dried at 105 °C to a constant mass (ISO 11272:1998).

The following chemical parameters were analyzed for forest floor and soil samples: pH was determined in a 0.01 M $CaCl_2$ suspension (ISO 10390:2005); organic carbon (C) was determined using a dry combustion method with a total carbon analyzer Analytic Jena multi EA 4000 Germany (ISO 10694:1995); total nitrogen (N) was analyzed using the Kjeldahl method (ISO 11261); mineral N was determined in 1 M KCl extraction using the spectrometric method (ISO 14256-2); mobile potassium (K_2O) and phosphorus (P_2O_5) were determined using a solution of ammonium lactate and acetic acid at pH 3.65–3.75 using the Égnér–Riehm–Domingo method.

2.3. Assessment of Tree Growth Indices

For the assessment of tree growth parameters, 10 circular study plots of 100 m^2 were distributed evenly at each study site. The tree diameter was measured using a tree caliper (precision 1 mm) at 1.3 m above ground (DBH—tree diameter at breast height) for all trees within all 10 study plots at each study site. For all trees, tree height (H) was measured using an ultrasound height measurer Vertex IV. To determine the stem quality of standing trees, depending on different soil cultivation methods applied before afforestation, the stem straightness was visually assessed. For the assessment of stem straightness, the simplified three-point scoring system was used, where a score of 1 indicated the straightest stem, while a score of 3 indicated the least straight (most crooked) stem. In total, 631 trees were measured in all study plots (see Table 1). The tree growth indices were assessed in late autumn of 2021.

2.4. Calculations and Statistical Analyses

The stocks of SOC, N, P, and K in the forest floor were calculated by multiplying the concentrations by the forest floor mass. The stocks in the 0–80 cm mineral topsoil (0–10 cm, 10–20 cm, 20–40 cm and 40–80 cm) were calculated according to the following equation [29]:

$$SOC_i = \rho_i (1 - \frac{\delta_i, 2mm}{100}) d_i C_i \times 10^{-1}, \quad (1)$$

where ρ_i is the bulk density of the <2 mm fraction in g·cm^{-3}, δi, 2 mm is the relative volume of the ≥2 mm fraction (percentage), d_i denotes the thickness of layer i in cm,

C_i denotes the C or nutrient concentration of layer i (mg·g^{-1}), and 10^{-1} is a unit factor (10^{-9} mg·Mg^{-1} × 10^{8} cm^{2}·ha^{-1}).

The nutrient stocks in each layer were calculated by summing the stocks calculated for individual 0–10 cm, 10–20 cm, 20–40 cm, and 40–80 cm mineral soil layers. The nutrient stocks for the entire mineral soil profile up to 80 cm depth were calculated by summing the corresponding stocks in the forest floor and mineral soil at 0–80 cm layer.

The data were analyzed for differences in concentrations and stocks between the stands representing different soil cultivation methods: deep ploughing, microsites, furrows, and non-ploughed soil. For the normality of the variables, the Shapiro–Wilk test was used, and the normality hypothesis was rejected with a 0.05 significance level. Therefore, the Kruskal–Wallis analysis of variance (ANOVA) test was used to ascertain the significant differences in variables between the sites representing different soil cultivation methods. The means are given with the standard error of the mean (±SE) in this study. The STATISTICA 12.0 (StatSoft. Inc., Tulsa, OK, USA, 2007) software with a level of significance of $p < 0.05$ was used.

3. Results

3.1. Changes in Forest Floor Mass and Chemical Properties

The highest mean pH value of the forest floor was obtained for the afforested sites cultivated by microsites (Table 2). The concentrations of OC in the forest floor of different sites were relatively similar, ranging between 214 g·kg^{-1} and 272 g·kg^{-1}. The significantly lowest concentration of OC was found in the forest floor of the sites cultivated by microsites, and there was no difference in OC concentrations between deep ploughing and non-ploughed sites. In deep ploughing sites, significantly higher concentrations of total N and total P in the forest floor were obtained in comparison to other land cultivation methods.

Table 2. Mean pH values and mean concentrations (±standard errors) of organic carbon (OC), total N, P, K, Ca, and Mg in the forest floor at the sites with different soil cultivation. Different letters indicate statistically significant differences in mean concentrations between the sites ($p < 0.05$).

Soil Cultivation	pH_{CaCl2}	Concentration (g·kg^{-1})			
		OC	Total N	Total P	Total K
Deep ploughing	4.6 ± 0.2 ^{ab}	227.7 ± 24.0 ^{ab}	7.8 ± 0.7 ^{ab}	0.8 ± 0.1 ^{b}	0.9 ± 0.1 ^{a}
Microsites	4.7 ± 0.2 ^{b}	214.3 ± 12.5 ^{a}	6.1 ± 0.5 ^{a}	0.6 ± 0.0 ^{a}	0.9 ± 0.0 ^{a}
Furrows	4.5 ± 0.2 ^{a}	271.8 ± 17.6 ^{b}	7.8 ± 0.5 ^{b}	0.7 ± 0.0 ^{b}	0.9 ± 0.1 ^{a}
Non-ploughed	4.6 ± 0.1 ^{ab}	220.1 ± 31.4 ^{ab}	6.1 ± 0.5 ^{a}	0.7 ± 0.0 ^{b}	0.9 ± 0.1 ^{a}

The highest mean mass of forest floor was found for the afforested sites cultivated by microsites (Table 3). The mean mass of forest floor accounted for deep ploughing sites was similar to that found for non-ploughed sites. Despite there being no significant differences in the stocks of OC and other nutrients (total N, P and K), a more specific response was obtained in the sites cultivated by microsites.

Table 3. Mean (±standard errors) forest floor mass and mean stocks of organic carbon (OC), total stocks of N, P, K, Ca, and Mg in the forest floor at the sites with different soil cultivation.

Soil Cultivation	Forest Floor Mass (t·ha^{-1})	OC	Total N	Total P	Total K
		(t·ha^{-1})		(kg·ha^{-1})	
Deep ploughing	15.8 ± 2.7	3.6 ± 0.7	131.6 ± 29.0	13.0 ± 3.1	14.4 ± 3.1
Microsites	21.3 ± 2.8	4.5 ± 0.7	133.2 ± 23.9	12.3 ± 1.3	18.5 ± 2.5
Furrows	14.6 ± 2.6	3.9 ± 0.8	117.0 ± 24.9	10.6 ± 2.3	13.9 ± 3.1
Non-ploughed	15.6 ± 3.6	3.6 ± 1.0	101.3 ± 29.9	11.2 ± 3.1	14.4 ± 3.2

3.2. Changes in Physical and Chemical Properties of Soil

For all studied sites, the mean bulk density of fine mineral soil in the 0–10 cm, 10–20 cm, 20–40 cm, and 40–80 cm soil layers varied in the narrow range of 1.1–1.4 g·cm^{-3} (Figure 2). In the 0–10 cm topsoil of afforested sites and naturally regenerated Scots pine forest on non-ploughed soil, the mean bulk density ranged from 1.1 to 1.3 g·cm^{-3}. A slightly higher mean bulk density was found for the deeply ploughed soil, the sites cultivated by microsites, and the non-ploughed sites compared to the sites cultivated by furrows. A mean bulk density of 1.1–1.4 g·cm^{-3} was obtained in the 10–20 cm soil layer. The highest bulk density was found in the sites cultivated by microsites, while the lowest bulk density was found in the sites cultivated by furrows. The bulk density in the 20–40 cm and 40–80 cm soil layers was 1.2–1.4 g·cm^{-3} and showed large similarity across all studied soil cultivation methods, including non-ploughed soil. Overall, there was no significant effect of different soil cultivation methods on soil bulk density. It is possible that the changes in bulk density could have been recorded at the beginning of the stand development and did not last 20 years.

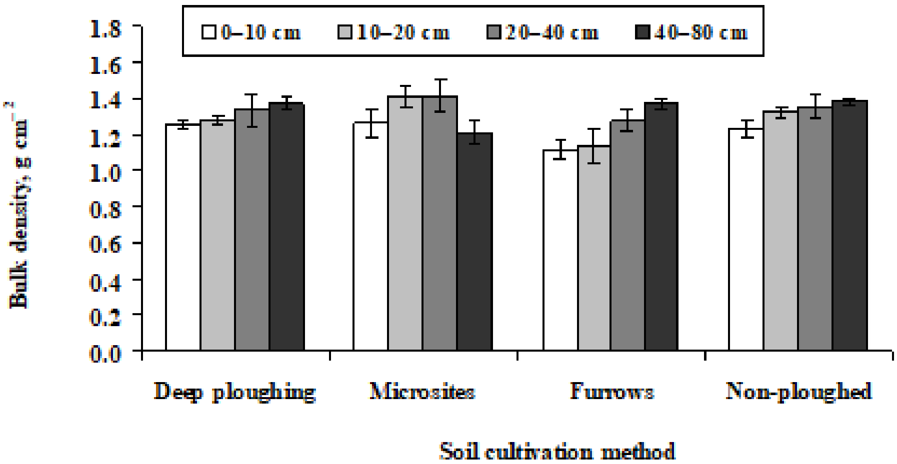

Figure 2. Mean bulk density (g·cm^{-2}) in mineral soil layers in the sites with different land cultivation 20 years post cultivation, including non-ploughed soil as a control.

The highest mean SOC concentrations of 8.4–9.8 g·kg^{-1} were found in the 0–10 cm soil layer of the sites cultivated by microsites, furrows, and non-ploughed sites. The mean SOC concentrations did not significantly differ between the 0–10 cm and 10–20 cm soil layers (Figure 3). A similar downward trend in SOC concentrations was observed at these three sites. The mean SOC concentrations decreased from 8.4–9.8 g·kg^{-1} (in 0–10 cm layer) to 4.7–5.7 g·kg^{-1} (in 40–80 cm layer). In deep ploughing sites, the mean SOC concentration was comparable at all soil depths up to 80 cm and amounted to 5.5–6.7 g·kg^{-1}.

The mean concentrations of total N in the 0–10 cm soil layer at deep ploughing sites were comparable to those obtained in the sites cultivated by microsites, but significantly lower than those found in the non-ploughed sites and the sites with furrows (Figure 3; Table 4). The mean concentration of total N was significantly 1.4–2.3 times higher in the 10–20 cm and 20–40 cm soil layers of deep ploughing sites compared to similar soil layers of non-ploughed sites. The soil cultivation by furrows also tended to increase the mean concentration of total N in the mineral topsoil compared to non-ploughed sites.

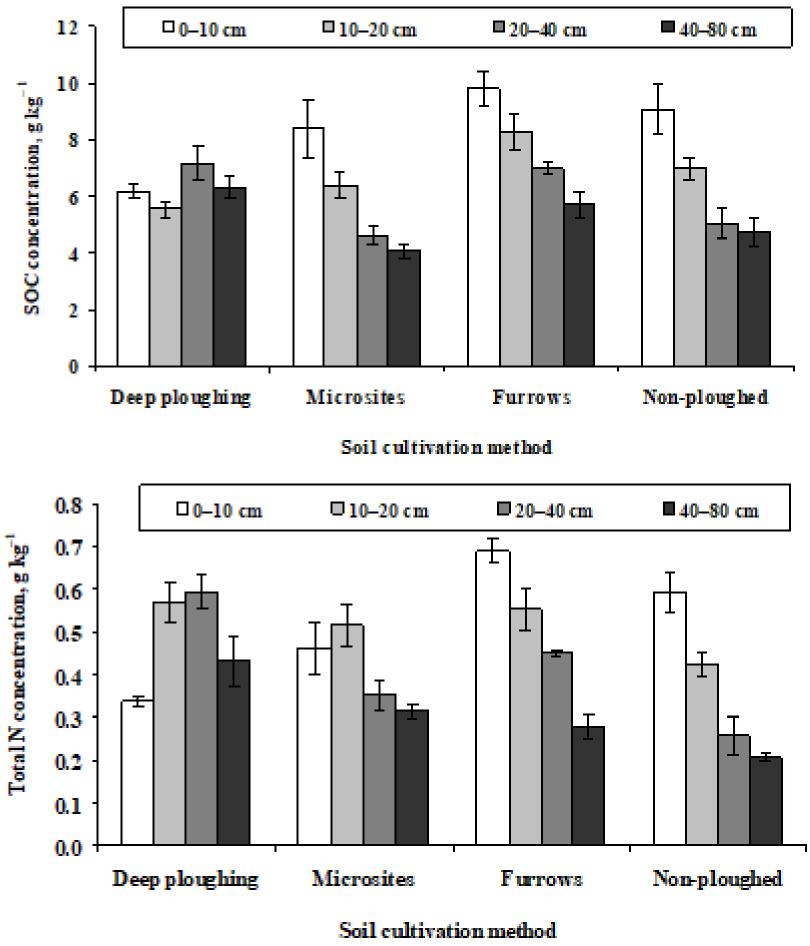

Figure 3. Mean concentrations (g·kg^{-1}) of soil organic carbon (SOC) and total nitrogen (total N) in the sites with different land cultivation 20 years post cultivation, including non-ploughed soil as a control.

The higher mineral N concentrations were found in the sites after soil cultivation by furrows in all studied soil depths up to 80 cm depth in comparison to non-ploughed sites (Table 4). This difference between the sites cultivated by furrows and non-ploughed ranged from 1.3–1.6 times in the 0–20 cm layer to 2.1–2.3 times in the 20–80 cm layer. In deep ploughing sites, the mineral N concentration was at the level of the concentration in non-ploughed sites with a significantly lower concentration in the 10–20 cm soil layer.

The mean concentration of total P was significantly 1.6–1.9 times higher in deeper mineral soil layers from 20 to 80 cm depth in the sites afforested after deep ploughing (Table 4). In the sites cultivated by furrows, the mean concentration of total P significantly increased in the mineral soil compared to non-ploughed soil with exception of the 0–10 cm topsoil. Significantly lower mean P_2O_5 concentrations were obtained in the 0–10 cm and 10–20 cm soil layers after deep ploughing and soil cultivation by making furrows in comparison to the non-ploughed site. In deep ploughing sites, significantly higher concentrations (1.6–2.1 times) of the mean P_2O_5 were found in 20–40 cm and 40–80 cm soil layers compared to the non-ploughed sites.

The concentration of total K was significantly higher (1.4 times) in the 0–10 cm mineral topsoil layer compared to the non-ploughed sites, but no changes were found in deeper soil layers up to 80 cm depth (Table 4). Slightly higher mean concentrations of K_2O were found in the 0–20 cm soil layer in the sites after deep ploughing and cultivation by microsites.

Table 4. Mean pH_{CaCl2} and mean concentrations of mineral nitrogen (N), total phosphorus (P), P_2O_5, total potassium (K), and K_2O in mineral soil. Different letters a, b, and c indicate statistically significant differences among the means in each soil layer within the sites representing different soil cultivation methods ($p < 0.05$).

Soil Cultivation Method	Mineral Soil Layer			
	0–10 cm	10–20 cm	20–40 cm	40–80 cm
	pH_{CaCl2}			
Deep ploughing	4.5 ± 0.2 ^{a}	4.6 ± 0.3 ^{a}	6.0 ± 0.9 ^{a}	6.9 ± 0.5 ^{a}
Microsites	5.0 ± 0.2 ^{b}	5.9 ± 0.1 ^{b}	6.1 ± 0.5 ^{a}	6.5 ± 0.5 ^{a}
Furrows	5.0 ± 0.3 ^{b}	6.0 ± 0.4 ^{b}	6.5 ± 0.4 ^{a}	7.0 ± 0.3 ^{a}
Non-ploughed	4.8 ± 0.7 ^{ab}	5.5 ± 0.6 ^{ab}	5.9 ± 0.3 ^{a}	6.4 ± 0.7 ^{a}
	Mineral N concentration (mg·kg^{-1})			
Deep ploughing	1.23 ± 0.20 ^{b}	0.74 ± 0.05 ^{ab}	1.04 ± 0.05 ^{b}	0.69 ± 0.11 ^{a}
Microsites	0.62 ± 0.13 ^{a}	0.40 ± 0.21 ^{a}	0.54 ± 0.20 ^{a}	0.46 ± 0.14 ^{a}
Furrows	2.22 ± 0.16 ^{c}	1.79 ± 0.02 ^{b}	1.90 ± 0.05 ^{c}	1.70 ± 0.11 ^{b}
Non-ploughed	1.41 ± 0.45 ^{b}	1.34 ± 0.21 ^{b}	0.89 ± 0.41 ^{ab}	0.74 ± 0.37 ^{a}
	Total P concentration (mg·kg^{-1})			
Deep ploughing	192.0 ± 6.0 ^{a}	253.7 ± 19.3 ^{b}	340.3 ± 13.3 ^{b}	326.0 ± 9.6 ^{b}
Microsites	251.0 ± 20.2 ^{b}	193.5 ± 21.3 ^{a}	115.8 ± 10.0 ^{a}	290.3 ± 78.7 ^{b}
Furrows	330.5 ± 15.5 ^{c}	314.8 ± 15.1 ^{c}	318.5 ± 22.2 ^{b}	360.0 ± 52.6 ^{c}
Non-ploughed	345.3 ± 19.6 ^{c}	260.0 ± 15.5 ^{b}	177.5 ± 31.4 ^{ab}	174.8 ± 14.0 ^{a}
	P_2O_5 concentration (mg·kg^{-1})			
Deep ploughing	48.7 ± 2.0 ^{a}	49.0 ± 4.2 ^{a}	100.3 ± 7.1 ^{b}	108.0 ± 11.5 ^{b}
Microsites	106.3 ± 12.3 ^{b}	71.3 ± 15.1 ^{b}	58.3 ± 22.9 ^{a}	102.0 ± 35.0 ^{b}
Furrows	56.5 ± 1.7 ^{a}	34.5 ± 5.4 ^{a}	51.8 ± 7.3 ^{a}	61.0 ± 4.5 ^{a}
Non-ploughed	135.0 ± 12.8 ^{c}	80.5 ± 14.6 ^{b}	48.8 ± 18.3 ^{a}	68.8 ± 8.3 ^{a}
	Total K concentration (mg·kg^{-1})			
Deep ploughing	705.3 ± 114.2 ^{b}	519.3 ± 31.9 ^{ab}	525.0 ± 38.7 ^{a}	672.3 ± 81.4 ^{a}
Microsites	496.0 ± 11.0 ^{a}	472.8 ± 11.5 ^{a}	557.3 ± 32.4 ^{a}	770.8 ± 31.0 ^{a}
Furrows	518.5 ± 16.3 ^{a}	566.8 ± 18.6 ^{b}	550.5 ± 26.1 ^{a}	706.0 ± 64.3 ^{a}
Non-ploughed	488.8 ± 7.5 ^{a}	482.0 ± 11.1 ^{a}	577.0 ± 88.4 ^{a}	692.3 ± 113.8 ^{a}
	K_2O concentration (mg·kg^{-1})			
Deep ploughing	49.3 ± 5.2 ^{ab}	33.0 ± 3.6 ^{ab}	29.7 ± 2.3 ^{ab}	30.0 ± 3.0 ^{b}
Microsites	51.5 ± 2.1 ^{b}	37.3 ± 1.1 ^{b}	38.3 ± 6.2 ^{b}	30.8 ± 5.2 ^{b}
Furrows	38.5 ± 1.0 ^{a}	26.8 ± 0.6 ^{a}	22.5 ± 1.0 ^{a}	18.8 ± 1.1 ^{a}
Non-ploughed	44.3 ± 6.9 ^{ab}	30.5 ± 5.2 ^{ab}	34.5 ± 9.1 ^{b}	28.5 ± 5.5 ^{b}

Figure 4 shows a strong positive relationship between total soil N concentration and the SOC concentration for the sites cultivated by furrows and non-ploughed sites (R^2 = 0.730–0.863, $p < 0.05$). However, other soil cultivation methods, especially deep ploughing, showed no relationship between total N and the SOC concentrations 20 years after afforestation.

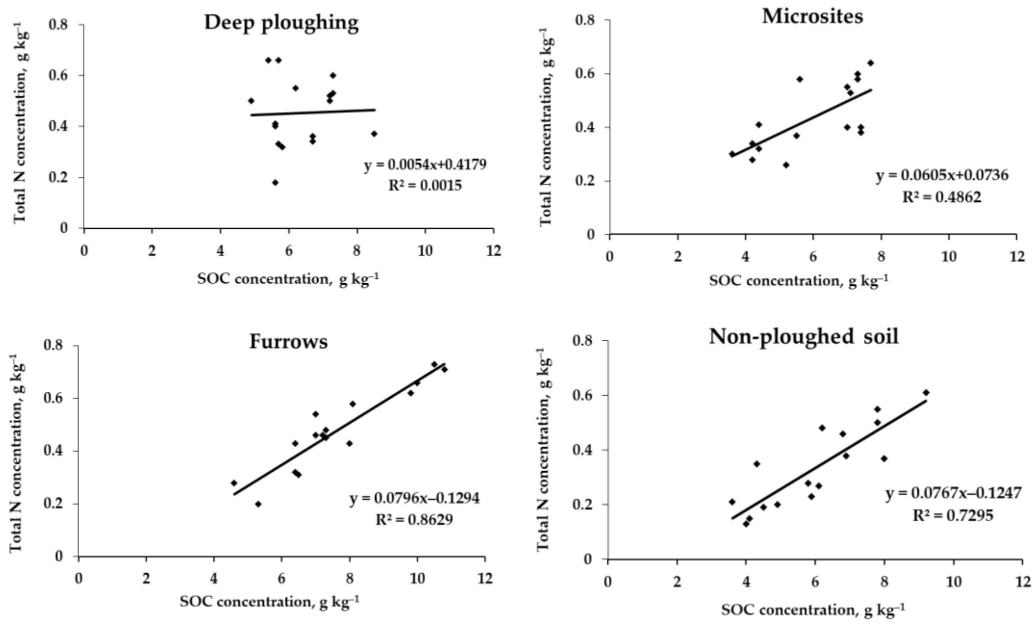

Figure 4. The relationship between carbon (SOC) and total nitrogen (N) concentrations (g·kg^{-1}) in the entire soil profile (0–80 cm) at the sites representing different soil cultivation methods.

Total SOC, N, and P stocks, obtained by summing the corresponding stocks in the forest floor and mineral soil at 0–80 cm layer, differed between the sites, representing different soil cultivation methods: deep soil ploughing, soil cultivation by 40 cm × 40 cm microsites, soil ploughing by making furrows, and non-ploughed soil (Figure 5). The highest total SOC stocks of 70–73 t·ha^{-1} were found in the deep ploughing sites and the sites cultivated by furrows. In the non-ploughed sites, the total SOC stock comprised 64 t·ha^{-1}. A significant difference between the studied sites was found in total N stock (forest floor together with 0–80 cm), which showed significantly higher N stocks (1.2–1.4 times) 20 years post deep ploughing compared to other soil cultivation methods applied prior to afforestation (Figure 5). Total N stock of 4.7 t·ha^{-1} was obtained in the deep ploughing sites, compared to a stock of 3.2 t·ha^{-1} in the non-ploughed sites. The smallest variations in the SOC and N stocks due to different soil cultivation methods were found in the forest floor.

Significantly higher total P stock, obtained by summing the P stock in forest floor and mineral 0–80 cm soil layers, was found in the deep ploughing sites (3273 kg·ha^{-1}) and the sites cultivated by making furrows (3290 kg·ha^{-1}) compared to the naturally regenerated forest (2232 kg·ha^{-1}) (Figure 5). In deep ploughing sites, the total P stocks increased mainly in the 20–40 cm and 40–80 cm soil layers but slightly decreased in the 0–10 cm and 10–20 cm topsoil layers. At the deep ploughing sites, the P stocks comprised 20% in the mineral 0–20 cm topsoil layer and 80% in the 40–80 cm subsoil layer, while this proportion was 35% and 65%, respectively, in non-ploughed sites. There were no significant differences in total P stock between the sites cultivated by microsites and non-ploughed sites. When comparing K stocks in the soil profile, obtained by summing the values in forest floor and mineral 0–80 cm soil layer, we found no significant differences between all the sites, including the non-ploughed sites. In the entire soil profile, total K stock varied in a narrow range of 6515–6650 kg·ha^{-1} in all studied sites.

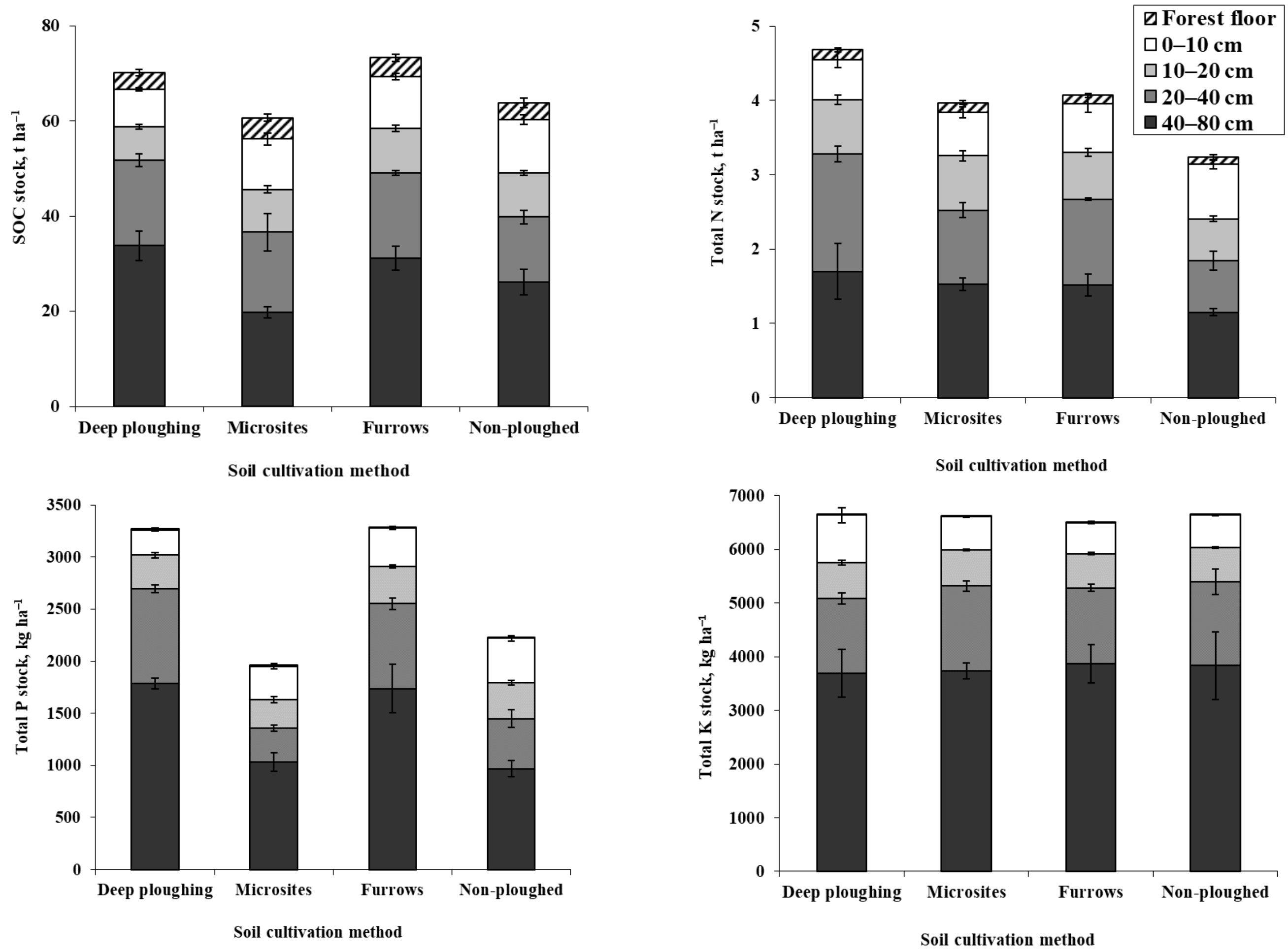

Figure 5. Distribution of total N and SOC stocks (t·ha^{-1}), and total P and K stocks (kg·ha^{-1}) in the soil profile, including the forest floor and mineral soil layers up to 80 cm depth, at the sites representing different soil cultivation methods.

3.3. Changes of Tree Growth Parameters

Basic tree growth parameters 20 years post soil cultivation are given in Table 5. The obtained results did not show statistically significant differences in mean tree diameter at breast height (DBH) between the studied sites. The mean DBH ranged between 13.3 cm and 14.0 cm in all sites with a slight increase in the sites cultivated by deep ploughing and microsites. The mean tree height (H) ranged between 9.1 m and 12.4 m, with the highest value found for the deep ploughing sites. In all afforested sites, the mean tree height was significantly larger than in the naturally regenerated Scots pine stand on non-ploughed soil. A significantly higher score of the mean stem straightness was obtained for trees grown in the deeply ploughed sites (Table 5).

Diverse relationships were obtained between tree DBH and H for the sites afforested with Scots pine trees after different soil cultivation and in the naturally regenerated Scots pine stand (Figure 6). In all cases, the tree DBH and H relationships showed a similar trend. The highest coefficient of determination was found for the naturally regenerated Scots pine stands on non-ploughed soil (R^2 = 0.657). While the lowest coefficient (R^2 = 0.411) was found for the sites afforested with Scots pine after the deep soil ploughing. Scots pine trees in the afforested sites grown on deeply ploughed soil had taller heights at the same stem DBH compared with the trees grown on non-ploughed soil. Therefore, a smaller tree size differentiation was observed in afforested sites in comparison with naturally developed Scots pine stands of a similar age under comparable site and climatic conditions.

Table 5. Tree growth parameters in the sites with different soil cultivation methods. Different letters show significant differences in mean concentrations between the sites ($p < 0.05$).

Soil Cultivation Method	Tree Number	Mean DBH * (cm)	Mean Height (m)	Mean Stem Straightness (Score)
Deep ploughing	183	14.0 ± 0.2 [a]	12.4 ± 0.1 [c]	1.15 ± 0.03 [b]
Microsites	142	14.0 ± 0.3 [a]	11.9 ± 0.2 [c]	1.08 ± 0.03 [ab]
Furrows	186	13.4 ± 0.2 [a]	11.0 ± 0.1 [b]	1.04 ± 0.01 [a]
Non-ploughed	120	13.3 ± 0.6 [a]	9.1 ± 0.3 [a]	1.07 ± 0.03 [a]

* DBH indicates the tree diameter at 1.3 m above the ground, often described as diameter at breast height.

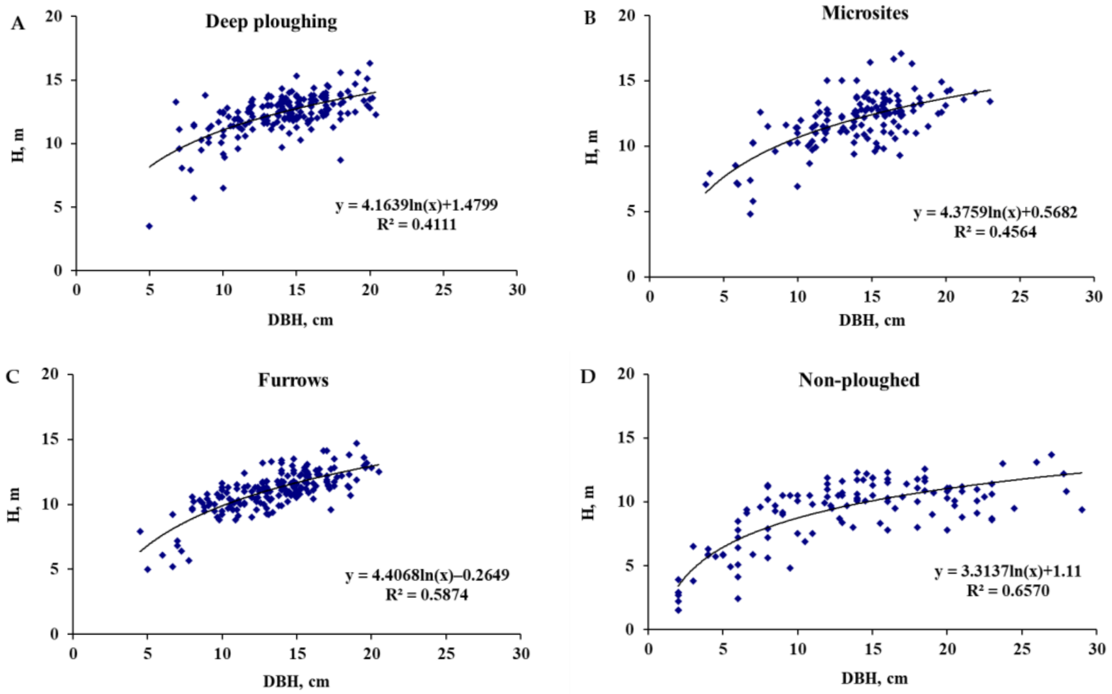

Figure 6. Relationship between tree height (H) and tree diameter at breast height (DBH) for the sites afforested with Scots pine after deep soil ploughing (**A**), soil cultivation by microsites (**B**), and furrows (**C**) 20 years post cultivation, and for the non-ploughed sites (**D**), representing a 20 years old naturally regenerated Scots pine stand.

4. Discussion

The present study was designed to determine the effect of different soil cultivation methods applied prior to afforestation of former agricultural land on the forest floor and mineral soil parameters, as well as basic tree growth parameters. The current study found no difference in organic carbon (OC) concentrations in the forest floor between deep ploughing and non-ploughed sites, but significantly higher concentrations of total N and P were obtained in afforested sites post deep ploughing. Another important finding was that the mean SOC concentration in mineral soil up to 80 cm depth in deep ploughing sites showed very little variability, indicating a different trend compared to other soil cultivation methods. Overall, our data showed the increase of total SOC stock in soil layers up to 80 cm depth, including the forest floor. The SOC stocks increased at deeper mineral soil layers in relation to the upper mineral soil layers. Significantly higher total SOC stocks (3–183%) were found 3–4 decades after the deep ploughing use in mineral soils [18,30]. It might be that deep ploughing can lead to higher SOC storage and continuous SOC sequestration in the topsoil [18]. The study by Nordborg et al. showed comparable results explaining higher SOC and soil N in the 30–50 cm and 50–70 cm layers at deeply ploughed plots [31]. In addition to C sequestration and the ability to retain carbon in the deeper soil layers, an increase in soil organic matter and higher SOC stock are important tools for soil fertility [32]. Several authors have been able to show that soil ploughing prevents mobilization and losses of deep and buried SOC [11,18].

Along with the entering of subsoil horizons at the soil surface, several soil parameters change. The studied sites afforested with Scots pine, representing different soil cultivation methods, had pH values ranging between pH 4.5 and pH 7.0 in mineral soil (see Table 3). In the soil at 0–20 cm depth, the pH values indicated relatively acidic soil (between 4.5 and 6.0), and this could have slowed the effect on forest litter decomposition. Reduced pH, SOC, and exchangeable Ca were also found in other studies [33]. The authors of [34] found decreased surface soil total N and extractable K and P after soil ploughing up to 30 cm. Soil mixing can affect the distribution of NO_3-N, causing more intensive leaching of higher NO_3 concentrations [35].

In the current study, deep ploughing had the highest effect on the relationship between SOC and total N, especially in comparison to non-ploughed sites. Initially, we hypothesized that the soil C:N ratio may reflect the soil cultivation intensity (especially deep ploughing vs. non-ploughed sites). In the present study, the C:N ratio of the forest floor varied between 30 and 36. The significantly lowest mineral soil C:N ratio was obtained in the sites afforested after deep soil ploughing. In the present study, a C:N ratio of 15.5 was found in the deep ploughing sites, and C:N ratios of 14.1 and 16.8 were found in the sites cultivated by making microsites and furrows, respectively. In all cases when soil cultivation was applied prior to afforestation, the C:N ratio was lower than in the non-ploughed soils, which amounted 19.3. These values were similar to those found in [36] (C:N ratio of 12–31) or in [37] (C:N ratio of 17–40). A C:N ratio of 20–30 indicates a balanced soil mineralization-immobilization process, and a lower ratio indicates faster nitrogen release to the soil [38]. Although we did not find comparable trends in how the C:N ratio depends on soil mixing in other studies, we assumed that soil mixing due to deep ploughing could have a disturbing effect on the C:N stoichiometry at least for 20 years after afforestation.

The results of this study also indicated a higher mean concentration of total N in the 10–40 cm mineral soil layer and a higher concentration of total P in the 20–80 cm layer at the sites afforested after deep ploughing and soil cultivation by furrows in comparison to non-ploughed sites. We also found that deep ploughing changed the relationship between the total N and the SOC concentration compared to non-ploughed sites. However, no significant changes were obtained for the concentration of total K. In accordance with the present results, previous studies have demonstrated that, due to deep soil ploughing, the mobile nutrients, including NO_3-N, are often re-distributed per soil profile [35]. Existing studies also show that the soil ploughing to 30 cm depth decreased total N and mobile K and P in the mineral soil layer [33]. Although we did not study it, the changes in the concentrations in mobile nutrients could potentially cause the increased leaching of these nutrients. Higher concentrations of nitrate and phosphate in the drainage water after soil cultivation were found in [39].

As previous studies showed, the major differences in chemical properties of mineral soil in the Scots pine plantations and the abandoned arable land are related to the accumulation and decomposition of forest floor and greater root mass in pine plantations [40]. However, there are strong indications that the use of different soil cultivation methods, including the deep soil ploughing technique, before afforestation of agricultural land, may cause differences in root development, especially the fine root mass and its vertical distribution [17,18].

In the context of young stand development, a potential effect of soil conditions, such as SOC and nutrient stocks, on tree height growth could be considered. We found no statistically significant effect of deep ploughing on mean DBH of Scots pine trees in comparison with other afforested and naturally regenerated sites 20 years post afforestation. However, mean tree height and stem straightness, taken as the stem quality index in this study, were significantly higher than obtained in the naturally regenerated stand. The obtained data do not allow stating that such a response occurred due to the different soil cultivation methods applied before planting. It could have been caused by intrinsic tree properties, genetic factors of the planted seedlings, and/or competition factors [41]. However, Sikström et al., in their study on conifers planted in clear cuttings in Fennoscandia, found that mechanical site preparation resulted in a 10–25% increase in conifer height 10–15 years after planting [42]. Furthermore, these authors explained that an increase in growth rate may be a temporary effect, but an increase in height is likely to persist. Generally, tree height can be explained by general soil fertility and nutrient availability, tree DBH, and stand density [43,44]. However, the stem straightness index obtained in our study may have been caused by deep soil ploughing. Otherwise, the greater differentiation in the size of trees in naturally regenerating stands was probably more due to the uneven tree regeneration intensity and early growth of individual trees or tree groups, and less due to the applied soil cultivation method.

The principal theoretical implication of this study is that, despite the significantly higher DOC and total N stocks in the subsoil in the deeply ploughed sites, there were no significant effects on Scots pine trees growth at least 20 years after afforestation. The knowledge obtained in this study could be potentially used as a mitigation tool regarding C sequestration or soil management prior to afforestation because the type of soil cultivation affects the basic properties of forest carbon and nutrient cycling. However, long-term measurements are required to identify the response of different soil cultivation methods to aboveground tree biomass development and belowground root production.

5. Conclusions

We conclude that the mean SOC concentration slightly varied within the mineral soil profile up to 80 cm, and the total N concentration was higher in the 10–40 cm layer than in other soil layers at deeply ploughed sites. Furthermore, in other sites, the SOC and total N concentrations decreased steadily with increasing soil depth. In deep ploughing sites, there were no clear relationships between SOC and total N concentrations in soil 20 years post cultivation, which was clear in other afforested sites and naturally developed Scots pine stand.

Deep ploughing prior to afforestation increased SOC and total N stocks in the subsoil compared to mineral topsoil. Deep ploughing and soil cultivation by furrows prior to afforestation resulted in higher total SOC and total N stocks in the entire soil profile up to 80 cm depth, including the forest floor.

Deep ploughing and soil cultivation by furrows caused an increase in total P concentration in the subsoil and an increase in total K in the upper mineral soil layer compared to non-ploughed soil. Significantly higher total P stock per entire profile was found for the deep ploughing sites and the sites cultivated by making furrows than in the naturally regenerated stand.

We found significantly larger tree height in the afforested sites than in the naturally regenerated Scots pine stand. The lowest tree differentiation in DBH was obtained in the deep ploughing sites. However, we assumed that this trend was caused by afforestation, the selection of seedlings, and the simultaneous start of tree growth, not by the soil cultivation method applied 20 years before afforestation.

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